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Renewable and Sustainable Energy Reviews
12 (2008) 1712–1724

RENEWABLE
& SUSTAINABLE
ENERGY REVIEWS

www.elsevier.com/locate/rser

Some statistical characteristics of monthly average wind speed at various heights

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Received 1 December 2006; accepted 9 January 2007

Abstract

The article, which is a segment of a complex wind energy examination, uses statistical methods to analyze the time series of monthly average wind speed in the period between 1991 and 2000 measured on seven Hungarian meteorological stations. Empirical distribution of measured monthly average wind speeds is approximated by theoretical distributions to claim that certain distributions are universal, i.e. independent of orography. We used one of them, the Weibull distribution, to generate the distribution of monthly average wind speeds on levels different from anemometer altitude as well, then we calculate the averages for the entire period and we fit a power function on them. Thus we can demonstrate a correlation between Hellmann's wind profile law and the Weibull distribution.

Keywords: Wind speed; Wind energy; Weibull distribution; Rayleigh distribution; Hellmann's power law

Contents

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1364-0321/$ - see front matter
doi:10.1016/j.rser.2007.01.014

1. Objective, database and methods

The article discusses a segment of a complex examination whose objective is to reveal the interdependence of parameters in wind energetic in order to outline a statistical stochastic model that may be useful in everyday wind energy utilization.

The hourly wind speed data for 10 Hungarian meteorological observatories in the period from 1991 to 2000 required for the energetic examination, which yielded the monthly average speeds as well, were provided by the Hungarian National Meteorological Service. Fig. 1 shows the geographical locations of the stations. The weather stations in Debrecen, Békéscsaba, Miskolc and Győr were relocated (at least once) in the period from 1971 to 2000 of the comprehensive study not restricted to wind speed examination. The relocation did not caused substantial change in the latitudes or longitudes of any stations concerned, but it significantly increased the elevation in Miskolc and the anemometer height in Békéscsaba. Both heights changed minimally in Győr. In Debrecen the station relocation caused no significant changes in basic wind statistics as one of our earlier studies showed [1], unlike to Győr where it did which can be shown by a simple homogeneity test of the wind data time series. The reason for this is probably the different environment at the new location. Hence we only used station data whose monthly data series can be regarded homogeneous in the period from January 1971 to December 2001. Thus anemometric conditions can be considered constant in the following stations: Debrecen, Szeged, Budapest, Pécs, Keszthely, Szombathely and Kékestető. Table 1 lists the exact geographical coordinates and the altitude of the wind-gauge above ground level for the observatories above.

We will analyze the originally measured, non-reduced forms containing trend and period of the time series of the monthly average speeds so that the results and conclusions might

Fig. 1. Geographical locations of the meteorological observatories comprising the database (in frame).

Table 1
Exact geographical coordinates of the observatories and anemometer altitudes

Observatory	φ	λ	h (m)	h_a (m)
			1991–2000	
Szombathely	47°16′	16°38′	219	9
Keszthely	46°46′	17°14′	117	15
Pécs	46°00′	18°14′	201	10
Budapest-L.	47°27′	19°13′	130	12
Szeged	46°15′	20°06′	83	9
Debrecen	47°30′	21°38′	111	10
Kékestető	47°52′	20°01′	1011	26

φ: latitude, λ: longitude, h: elevation, h_a: anemometer altitude above ground level.

be directly usable in the practice of wind energy production. We approximate the empirical distribution of the time series with theoretical distributions used for wind climatological analysis. We will use one of them, the Weibull distribution, to produce the distribution of monthly average wind speed at levels different from anemometer altitude. We also calculate the average wind speeds in the whole period in question at the same altitudes and we match power functions to those averages.

2. Distribution of monthly average speeds at measurement altitude

We carried out the actual distribution tests to show probable orographic differences at anemometer altitude. We started with fitting the Weibull distribution, which plays central part in the study of wind climate and wind energy [2–11], perhaps due to the fact that once its parameters are calculated for a given altitude, we can obtain parameters for different levels and learn the distribution of wind speed at those levels too. We discussed such analysis of daily average wind speed values earlier [12]. There we concluded that in Hungary the above distribution becomes more frequent in case of a relatively homogeneous flow, that is at higher altitudes (cf. [13]), and under certain macrosynoptic situations. Other studies based their definition of various wind statistics on the assumption that the Weibull distribution approximates wind speed [14–16].

Density function of the Weibull distribution in its simplest form is [17]

$$f(x) = f(x; k, c) = \frac{k}{c}\left(\frac{x}{c}\right)^{k-1} \mathrm{e}^{-(x/c)^k}, \tag{1}$$

where c is a so-called scale parameter (m/s) and k is the shape parameter (a dimensionless number). If their values at z_a anemometer altitude are c_a and k_a, then at a $z \neq z_a$ level

$$c_z = c_a(z/z_a)^n, \tag{2}$$

$$k_z = k_a[1 - 0.088\ln(z_a/10)]/[1 - 0.088\ln(z/10)] \tag{3}$$

and exponent n is

$$n = [0.37 - 0.088\ln c_a]/[1 - 0.088\ln(z_a/10)]. \tag{4}$$

Several methods have been formulated to define $c = c_a$ and $k = k_a$ parameters valid at the altitude of wind measurement. Here, we will use three of them, based on [17] and we also show Matyasovszky's method [13].

Method 1 is essentially a linear regression on transformed values of the center of speed intervals (v_i) and the respective cumulate frequency (p_i). The transformations are the following:

$$x_i = \ln(v_i), \tag{5}$$

$$y_i = \ln[-\ln(1 - p_i)]. \tag{6}$$

c and k can be defined from the constants of the $y = a + bx$ regression equation as $c = \exp(-a/b)$, $k = b$.

Method 2 is based on the known lower and upper quartiles (q_1 and q_3) and the median (q_2) of wind speed. It is obviously follows that

$$k = \ln(\ln 0.25/\ln 0.75)/\ln(q_3/q_1) = 1.573/\ln(q_3/q_1) \tag{7}$$

and

$$c = q_2/(\ln 2)^{1/k}. \tag{8}$$

Method 3 goes back to momentum estimation. On condition that we know the average wind speed (v_m) and deviation (s_n),

$$k = (s_n/v_m)^{-1.086}, \tag{9}$$

$$c = v_m/\Gamma(1 + 1/k), \tag{10}$$

where s_n/v_m is the variational coefficient and $\Gamma(x)$ is the gamma function.

Method 4 is the momentum estimation of the parameters [13]. After the following transformation of the parameters and ξ stochastic variable assumed to fit Weibull distribution:

$$d = \frac{1}{k}, \quad \eta = \left(\frac{\xi}{c}\right)^k \tag{11}$$

we get the following estimated values for d and c:

$$d^2 = \frac{6}{\pi^2}\frac{1}{n-1}\sum_{i=1}^{n}(\ln x_i - \overline{\ln x})^2, \tag{12}$$

$$\ln c = \overline{\ln x} - \varepsilon d, \tag{13}$$

where x_i is the sample elements, n is their number, $\overline{\ln x}$ is the average of their logarithm and ε is the so-called Eulerian constant $\varepsilon \approx 0.5772$.

If $k = 2$, then we got the Rayleigh distribution, a special case of the Weibull distribution [18] whose distribution density is

$$f(x) = f(x; c) = \frac{2x}{c^2}\mathrm{e}^{-(x/c)^2}. \tag{14}$$

The expected value of a probability variable with such a distribution is

$$\mu = \frac{c\sqrt{\pi}}{2}, \tag{15}$$

that is, parameter c is in proportion to the average. The arithmetic average of value k measured in 13 Hungarian locations is 1.44 [14]. This fact and the easy estimation of its parameter is the reason why that distribution is often used to approximate the empirical distribution of wind observations [5–7,14,16,19–21].

We have also tested the probability distributions below to approximate frequency distribution of monthly average wind speed:

Normal distribution, whose distribution density is

$$f(x) = f(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} \mathrm{e}^{-(x-\mu)^2/2\sigma^2}. \tag{16}$$

Its parameters are the μ expected value and the σ standard deviation of the ξ probability variable.

- Log-normal distribution, whose distribution density is

$$f(x) = f(x;\mu,\sigma) = \frac{1}{\sigma x\sqrt{2\pi}} \mathrm{e}^{-(\ln x-\mu)^2/2\sigma^2.} \tag{17}$$

Its parameters are the μ expected value and the σ standard deviation of the $\ln\xi$ probability variable ($\xi > 0$).

- Square-root normal distribution, whose distribution density is

$$f(x) = f(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi x}} \mathrm{e}^{-(\sqrt{x}-\mu)^2/2\sigma^2.} \tag{18}$$

Its parameters are the μ expected value and the σ standard deviation of the $\sqrt{\xi}$ probability variable ($\xi \geqslant 0$).

- Gamma distribution, whose distribution density is

$$f(x) = f(x;\lambda,p) = \frac{\lambda^p}{\Gamma(p)} x^{p-1} \mathrm{e}^{-\lambda x} \quad \text{if } x > 0, \tag{19}$$

$$f(x) = f(x;\lambda,p) = 0 \quad \text{if } x \leqslant 0, \tag{20}$$

where $\Gamma(p)$ is the gamma function. The μ expected value and the σ^2 of the standard deviation of a probability variable with such a distribution is

$$\mu = \frac{p}{\lambda}, \quad \sigma^2 = \frac{p}{\lambda^2} \tag{21}$$

that is parameters p és λ is easy to estimate [13,19].

Table 2
Good fittings at the significance level of 0.05 (+)

1991–2000	Type of distribution					
	Weibull	Rayleigh	Normal	Log-normal	Sq-root normal	Gamma
Debrecen				+	+	+
Szeged	+		+	+	+	+
Budapest	+		+	+	+	+
Pécs	+		+		+	+
Keszthely	+		+	+	+	+
Szombathely	+		+	+	+	+
Kékestető	+		+	+	+	+

We performed the χ^2 goodness-of-fit test at the significance level of 0.05. Table 2 shows the results in case of *measured* data. The + sign indicates cases where the approximation proved good at least the abovementioned significance level.

The Weibull distribution proved good enough approximation only at the significance level of 0.10, while the Rayleigh distribution, contrary to expectations and literary references, proved to be useless in the case of monthly average wind speeds. But the Weibull parameters that fit best are as follows:

	c	k
Debrecen	2.80	6.72
Szeged	3.29	7.04
Budapest	2.59	8.12
Pécs	3.17	5.44
Keszthely	2.07	5.04
Szombathely	3.56	5.81
Kékestető	4.50	5.29

Where k values are significantly higher than 2.

Square-root normal and gamma distributions proved to give a good approximation for all stations according to Table 2. The universality of these distributions is apparent, rather than any visible orographic difference. It is salient to opt for the square-root normal distribution to describe the frequency distribution of the average monthly measured wind speeds at anemometer altitude due to the difficulty of parameter determination.

3. Approximating the distribution of monthly average speeds at different altitudes

If we wish to define the distributions at various altitudes other than anemometer height, a segment of a complex examination can rely on the properties of the Weibull distribution which we described by Eqs. (2)–(4) and analyzed above. That is what we will attempt below. We take z_a values from Table 1, and let $z = 20$, 40, 60, 80 and 100 m. We used the best fitting parameters, which, however, were under the 0.9 acceptance level, for Debrecen.

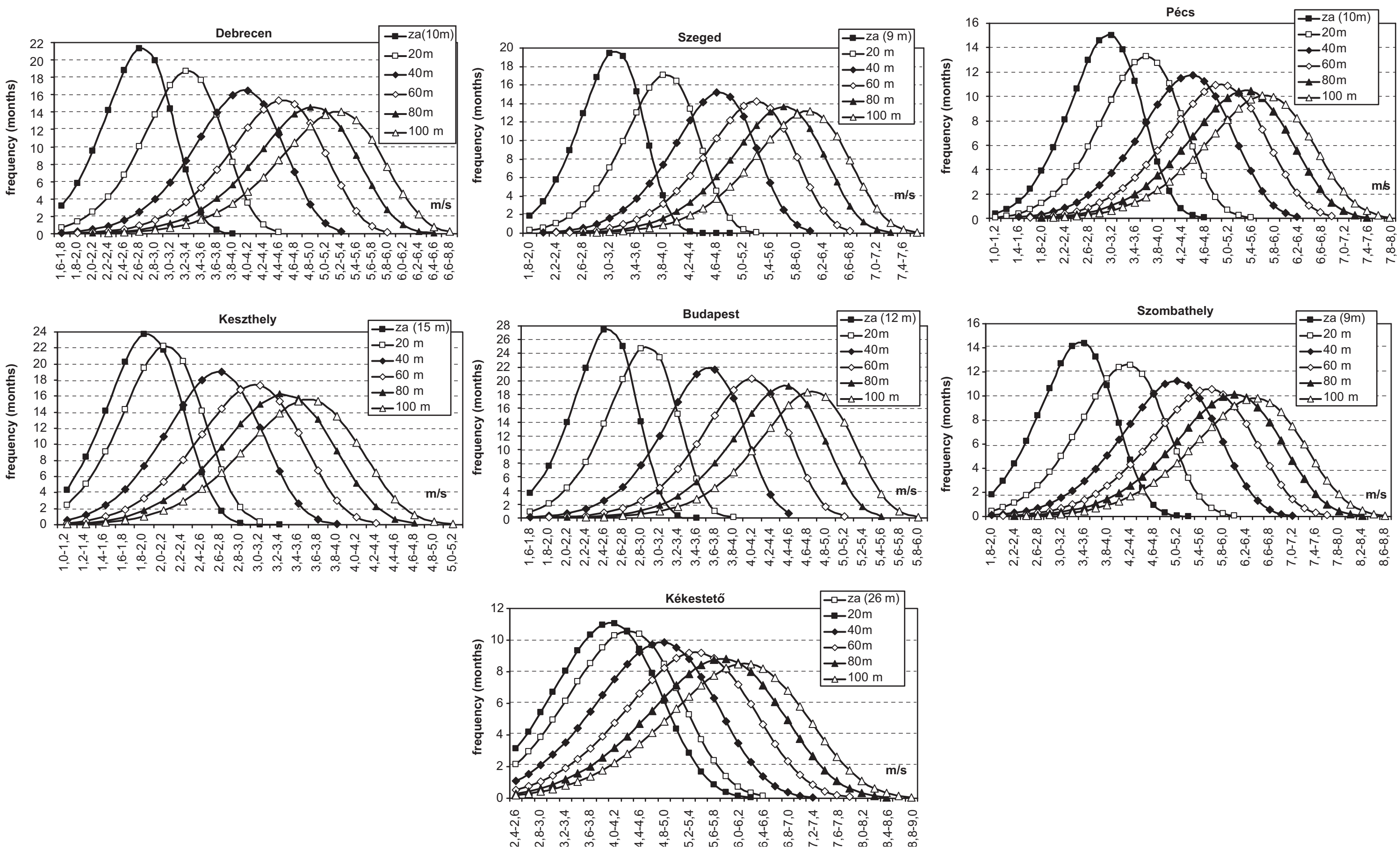

Fig. 2. Distribution of monthly average wind speeds in each observatories at anemometer altitude (z_a) and at five additional levels in the period between 1991 and 2000.

Table 3
Parameters and basic statistical data of the Weibull distribution which describes the distribution of monthly average wind speeds at z_a anemometer altitude and at five other levels in the period between January 1991 and December 2000

		Debrecen	Szeged	Budapest	Pécs	Keszthely	Szombathely	Kékestető
	z_a (m)	10	9	12	10	15	9	26
	n	0.28	0.26	0.29	0.27	0.32	0.26	0.26
z_a (m)	c_a	2.80	3.25	2.59	3.17	2.01	3.56	4.50
	k_a	6.72	7.18	8.12	5.44	5.41	5.81	5.29
	mean	2.7	3.1	2.5	2.9	1.9	3.3	4.3
	Var.coeff.	0.17	0.17	0.15	0.21	0.23	0.20	0.20
	Variance	0.47	0.51	0.38	0.61	0.43	0.65	0.85
20	c_z	3.40	4.01	3.01	3.82	2.21	4.36	4.21
	k_z	7.16	7.72	8.50	5.80	5.56	6.25	5.16
	Mean	3.2	3.8	2.8	3.5	2.0	4.1	3.9
	Var.coeff.	0.16	0.15	0.14	0.20	0.21	0.18	0.22
	Variance	0.52	0.57	0.40	0.70	0.42	0.75	0.85
40	c_z	4.13	4.82	3.68	4.60	2.75	5.21	5.03
	k_z	7.66	8.26	9.09	6.20	5.94	6.68	5.52
	Mean	3.9	4.5	3.5	4.3	2.6	4.9	4.6
	Var.coeff.	0.15	0.14	0.13	0.19	0.19	0.17	0.21
	Variance	0.60	0.65	0.46	0.80	0.49	0.85	0.96
60	c_z	4.62	5.36	4.14	5.13	3.13	5.78	5.59
	k_z	7.98	8.61	9.48	6.46	6.19	6.97	5.75
	Mean	4.4	5.1	3.9	4.8	2.9	5.4	5.2
	Var.coeff.	0.15	0.14	0.13	0.18	0.19	0.17	0.20
	Variance	0.64	0.70	0.50	0.86	0.54	0.90	1.03
80	c_z	5.01	5.79	4.50	5.54	3.44	6.22	6.03
	k_z	8.23	8.87	9.77	6.66	6.39	7.18	5.93
	Mean	4.7	5.5	4.3	5.2	3.2	5.8	5.6
	Var.coeff.	0.14	0.13	0.12	0.17	0.18	0.16	0.19
	Variance	0.68	0.73	0.52	0.90	0.58	0.95	1.08
100	c_z	5.33	6.14	4.81	5.89	3.69	6.59	6.38
	k_z	8.43	9.09	10.01	6.83	6.54	7.36	6.08
	Mean	5.0	5.8	4.6	5.5	3.4	6.2	5.9
	Var.coeff.	0.14	0.13	0.12	0.17	0.18	0.16	0.19
	Variance	0.71	0.76	0.55	0.94	0.61	0.98	1.12

First, we determined the parameters c_z and k_z using the equations mentioned above. Using those parameters we produced the distributions for altitudes z shown in Fig. 2 together with the Weibull distributions fitted to level z_a. Table 3 shows the average values, the standard deviations and the coefficients of variation for each altitude levels. We used the relations (9) and (10) to determine these on higher levels.

Fig. 3 illustrates the dependency of average speeds calculated for the whole period ($v_{z\text{mean}}$) on altitude based on the data in Table 3. We fitted a power function on the calculated values at six points, that is $v_{z\text{mean}} = az^{\alpha}$. Thus we can formulate the so-called Hellmann relation for v_1 and v_2 average speeds at altitudes z_1 and z_2 in the form

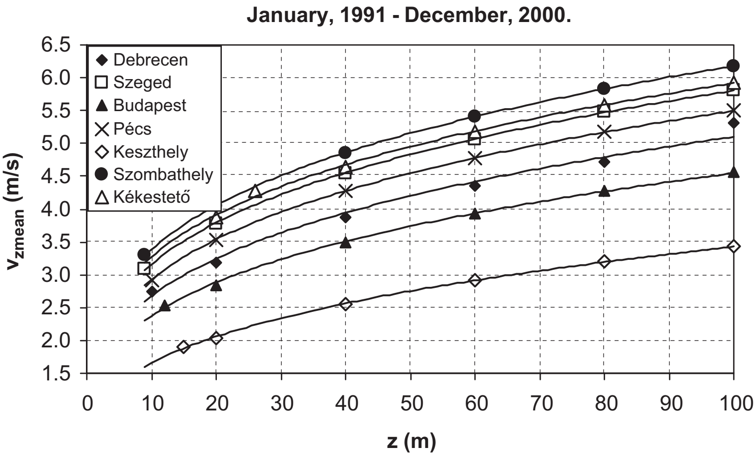

Fig. 3. Average wind speeds (points) calculated for the whole measurement period and the power function fitted on them.

conventionally used in wind energy research as

$$\frac{v_1}{v_2} = \left(\frac{z_1}{z_2}\right)^{\alpha}. \tag{22}$$

Theoretically, relations (22) and (2), as the scaling factors also have the m/s dimension, must be the same, i.e. $n = \alpha$. This is also indicated by the results of the previous fitting for α, which are the following: Debrecen 0.27, Szeged 0.26, Budapest 0.28, Pécs 0.27, Keszthely 0.32, Szombathely 0.26, Kékestető 0.26. They show good correspondence with the data for n in Table 3. That is defining the value of α using some other methods, e.g. measuring wind speeds at different levels; we learn a very important Weibull parameter too.

One may get very good approximations with $\alpha = 0 \cdot 2$ up to 200 m according to [21–27] who used the same formula. We can, however, further adjust the value of α according to surface friction based on data from meteorological observation towers and wind energetics measurements. Kajor [28,29] claims this value to alternate between 0.14 over level sea and 0.34 over rough dry-land areas. Radics [16] thinks the exponent to be 0.14 over flat area or surface of water, 0.2 over ragged downy surface, and 0.28 over settlements. Sembery and Tóth's work [30] offers the most detailed data concerning the exponent as being 0.12 over level field, 0.16 over open terrain, 0.25 over level woodland, 0.35 over cities with small buildings and 0.50 over cities with tall buildings. These data are similar to exponents by Gipe [20]: 0.1 over water or ice, 0.14 over low grass or steppe, 0.2 over rural with obstacles, 0.25 over suburb and woodlands and by Ozdamar et al. [31]: 0.14 over open sea, coast, 0.18 over open land, fields, 0.28 over woodland and city, 0.4 over city with high buildings. Péczely [32] also notes that the exponent α depends on wind speed and air stratification as well as on surface raggedness. Whereas he thinks it can be taken as 0.3 over grass-covered surface at medium wind speed.

We performed studies to determine the value of exponent α based on the wind speed and direction data at 20, 50 and 150 m from tower measurements in Paks in 2000 and 2001

Table 4
Estimation of exponent α using different methods

Yearly means and variances of exponent α calculated from different heights (20, 50, 120 m) and by different methods (1, 2, 3)			1. From the daily average wind speeds	2. From the daily averages of hourly exponents	3. From the averages of wind directional exponents
2000	Mean	20→50	0.43	0.50	0.50
		20→120	0.44	0.47	0.46
		50→120	0.44	0.43	0.43
	Variance	20→50	0.10	0.15	
		20→120	0.09	0.11	
		50→120	0.12	0.14	
2001	Mean	20→50	0.41	0.45	0.45
		20→120	0.43	0.45	0.44
		50→120	0.46	0.45	0.45
	Variance	20→50	0.10	0.12	
		20→120	0.09	0.10	
		50→120	0.12	0.13	

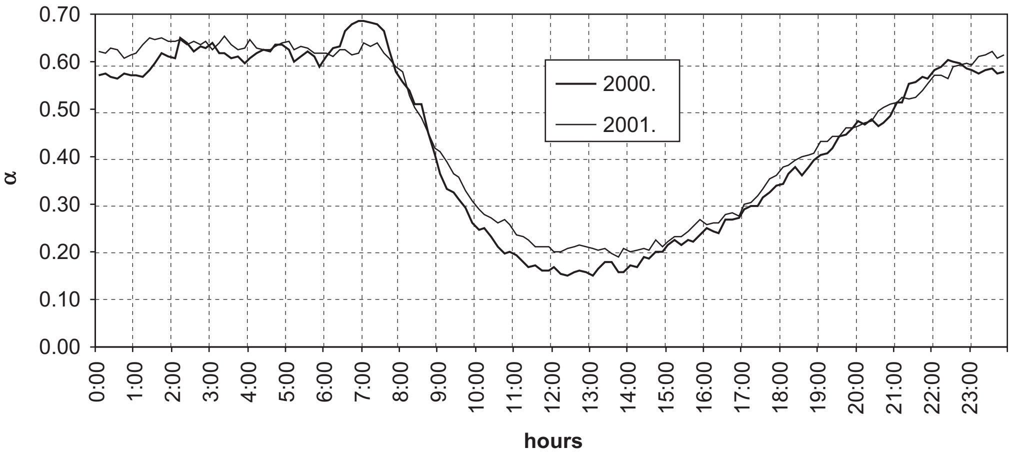

Fig. 4. Sample daily pattern of the Hellmann exponent (α) at 120 m height calculated from 50 m in Paks, in years 2000 and 2001.

[15,33,34]. This database consists of 10 min average values for both years. We used three methods to determine α, whose generalizations can be found in Table 4.

1. We used the exponent determined on the basis of daily *average wind speeds* calculated for the different levels to achieve annual averages and deviations (see column four of the table).
2. We determined the value of α for each measurement time, out of which we calculated first the hourly and daily then the annual averages. The latter is shown in the appropriate column of the table, while Fig. 4 is a sample daily curve. That eventually illustrates the dependency of the exponent on air stability, air balance (that is wind speed): its minimum falls around the time of the hottest time (fastest wind) while it

hardly changes when stratification is stable (by night). Thus it shows good correspondence with the daily course of the relative frequency of stable and unstable stratifications [16].
3. We also determined the average exponent values for each wind directions to calculate an average independent of wind direction (see in the last column).

The values published in the accessible literature are likely to define a very narrow range for α. It does not cause big error to ignore the daily variation of α, that is its dependence on temperature stratification and wind speed, in our calculations [35,36]. We must, however, pay particular attention to its variation depending on the wind direction. What remains once we filter various disturbances, for example the windscreen factor of the observation tower, is the effect of the individual orography at a given direction, therefore we might extrapolate an exponent calculated this way for areas with similar characteristics.

It is only Debrecen and Pécs of all seven observation locations where anemometers are deployed in the standard 10 m altitude, so we had to determine the average wind speed on that level for the rest of the stations to ensure comparability by the help of the fitted power function ($z = 10\,\mathrm{m}$) and formula (22). In the latter case we used z_a altitude together with wind speed calculated from local measurement data we considered more accurate than approximate wind speed substitution. The results are as follows: Debrecen 2.74, Szeged 3.16 or 3.17, Budapest 3.37 or 2.41, Pécs 2.93, Keszthely 1.65 or 1.67, Szombathely 3.38 or 3.38 and Kékestető 3.28 or 3.34 m/s. The double check results from the power function caused 0.04 and 0 m/s deviation in case of Debrecen and Pécs, respectively.

4. Conclusions

Finally, the most important conclusions of our examination are the following.

- The distribution of original average monthly speeds containing trend and period can always well approximated by the square-root normal and the gamma distributions irrespective of the orographic environment. Normal and log-normal distributions, as well as the Weibull distribution share the same property with only one stations expected in each case. Special case of the latter, in which it is substantially simpler to determine parameters, the Rayleigh distribution cannot be applied to the time series in question.
- The distribution of average monthly speeds at altitudes other than measurement level can be produced by the Weibull distribution. The average of monthly averages falling in the highest frequency interval is the greatest in Szombathely and smallest in Keszthely at all altitudes.
- The relationship between n, one of the parameters of the Weibull distribution, and the Hellmann exponent (α) is established, but it requires further investigation. For α depends on several surface properties or parameters while n only depends on the scaling factor and altitude of the measurement level.

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